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FILTER-WHEEL SOLAR SIMULATOR

*by Joseph Mandelkorn, Jacob D. Broder,
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SUMMARY

A simple low-cost filter-wheel solar simulator for measurements of characteristics of silicon solar cells is described. The simulator has been used to determine outer-space short-circuit currents and to analyze spectral response of cells and performance of cells with antireflective coatings.

Values of equivalent outer-space short-circuit currents for unbombarded and electron-bombarded cells were measured by using the simulator and were compared with values from airplane flights. The values agreed within 2 percent. Correction factors for the short-circuit current of proton-bombarded cells, which compensate for the low-level illumination of the filter-wheel simulator, were determined.

The calibration and the basic concepts of operation of the filter-wheel simulator are derived from the work of H. K. Gummel at the Bell Telephone Laboratories. Although the simulator was calibrated by using only silicon cells, outer-space short-circuit currents of gallium arsenide cells as measured by the simulator and by airplane flights agreed within 4 percent.

INTRODUCTION

During the past year, two types of commercial solar simulators for the measurement of solar cells have become available; one type uses a xenon light source, whereas the other uses a combination tungsten-xenon light source. Solar-cell measurements have also been made by using carbon-arc simulators. A fourth type of simulator, the filter-wheel simulator, was developed and calibrated at the Bell Telephone Laboratories by H. K. Gummel (ref. 1). A modified version of the BTL filter-wheel simulator designed at Lewis is the simplest, most economical, and most versatile of the simulators.

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CONSTRUCTION OF FILTER-WHEEL SIMULATOR

The Lewis simulator consists of eight sharp cutoff filters mounted along the periphery of a vertical wheel. A tungsten light source and a holder for two silicon solar cells are on opposite sides of the wheel. One of the two cells in the holder is permanently mounted and monitors the intensity of the light output of each filter when it is brought into position in front of the light source. The second cell is the one to be measured. The filter wheel is rotated by an electric motor with a microswitch arrangement, which permits each filter to be centered between the light source and the cell holder as long as the operator desires. The currents generated in the monitor and test cells by the nearly monochromatic illumination are passed through two sensitive current meters. The meter readings are recorded by the operator. From the ratio of the two readings a value of equivalent outer-space current for the test cell in the specific wavelength region of the solar spectrum centered about the filter pass band is calculated. The filters and calibration method used are essentially identical to those developed by Gummel, and the Lewis simulator was calibrated with standard cells supplied through the courtesy of the Bell Telephone Laboratories. As a result, the Lewis and BTL simulator measurements have agreed to within 2 percent.

MEASUREMENT OF SOLAR-CELL SHORT-CIRCUIT CURRENTS

The short-circuit current of a solar cell throughout a series of bombardments was computed with the use of the Lewis simulator and is given in table I. The first column lists the wavelengths of the various filters in the simulator. The second column lists the equivalent outer-space currents of the cell for the wavelength region centered about the filter wavelength. The cell was bombarded with a dose of 1.2×10^{15} 1-Mev electrons per square centimeter before current was measured. The mathematical addition of the currents for each filter yields the total short-circuit current shown. As the cell is bombarded with higher doses, the currents at the longer wavelengths decrease as shown in the third and fourth columns, whereas

TABLE I. - OUTER-SPACE CURRENT COLLECTION AT VARIOUS WAVELENGTHS OF SOLAR SPECTRUM

[Superblue boron-doped 10-ohm-cm silicon cell bombarded with 1-Mev electrons.]

Wavelength of filter, microns	Dose, 1-Mev electrons/sq cm			Current loss, ma
	1.2×10^{15}	4.8×10^{15}	1.5×10^{16}	
	Open-circuit voltage, v			
	0.475	0.455	0.450	
	Efficiency, percent			
	7.5	6.75	6	
	Current in wavelength region, ma			
0.95	2.97	2.26	1.95	---
.9	7.87	6.35	5.63	---
.8	10.9	9.76	9.15	---
.7	11.9	11.33	11.04	---
.6	9.6	9.44	8.77	-0.8
.5	5.79	5.8	5.8	0
.45	4.29	4.25	4.20	0
.4	4.44	4.44	4.44	0
	Total 57.76	Total 53.63	Total 50.98	

there is no loss in current in the short wavelength region extending up to 0.6 micron. This difference illustrates the importance of the current collected by a cell in the short-wavelength region insofar as radiation damage resistance is concerned.

COMPARATIVE SIMULATOR MEASUREMENTS

It has been suggested that simulators be compared by analyzing the measurements made by each simulator of short-circuit currents on a selected group of solar cells. Such a comparison, however, cannot be expected to reveal maintenance costs and problems of calibration, stability, and uniformity of illumination of the different simulators. Measurement comparisons can only reveal differences in the spectral content of the simulators.

TABLE II. - COMPARISON OF SHORT-CIRCUIT CURRENT OF UNBOMBARDED SILICON CELLS

Deviation, percent	Simulator 1 (a)	Simulator 2 (a)	Lewis carbon arc (b)
	Number of cells within percentage deviation of BTL simulator readings		
0 to 2	3	4	4
2 to 4	4	3	7
4 to 7	10	11	6
Over 7	1	0	1

[a]Measurements from simulators 1 and 2 always higher than BTL measurements.

[b]Short-circuit current measured under carbon arc illumination lower than BTL measurements in every instance.

To demonstrate the foregoing, comparative measurements are shown in table II. The short-circuit current values of 18 unbombarded cells measured on the BTL simulator were used as standard values.

The currents of these cells were also measured under three other simulators, and percent deviations of these values from the standard values were calculated. The values of current for each cell measured by simulators 1 and 2 agreed to within 1 percent in nearly all cases, and readings of these simulators were always higher than the BTL readings. The BTL readings were chosen as the standards for comparison because of the excellent agreement between BTL and airplane-flight values of short-circuit current for the cells (ref. 2).

TABLE III. - COMPARISON OF SHORT-CIRCUIT CURRENT OF HEAVILY BOMBARDED SILICON CELLS

[Dose, 1.5×10^{16} 1-Mev electrons/sq cm.]

Deviation, percent	Simulator 1 (a)	Simulator 2
	Number of cells within percentage deviation from Lewis readings	
0 to 2	6	13
2 to 4	10	6
4 to 7	3	0

[a]Simulator 1 measurements all higher than those of Lewis simulator.

Table III contains a comparison of measurements from simulators 1 and 2 for heavily bombarded cells. Simulator 2 measurements for heavily bombarded cells agree more closely with Lewis filter-wheel simulator readings than those for unbombarded cells, whereas simulator 1 measurements are

TABLE IV. - COMPARISON OF SHORT-CIRCUIT CURRENT OF HEAVILY BOMBARDED SILICON CELLS MEASURED BY SIMULATORS 1 AND 2

[Dose, 1.5×10^{16} 1-Mev electrons/sq cm.]

Deviation, percent	Number of cells within percentage deviation from simulator 2 readings (a)
0 to 2	1
2 to 4	13
4 to 7	5

[a]All measurements from simulator 1 were higher than those from simulator 2.

appreciably higher than those for unbombarded cells. (As has been pointed out, Lewis and BTL simulator readings agree closely and are therefore interchangeable.) The currents of unbombarded cells depend primarily on collection from the long-wavelength region of the solar spectrum, whereas currents for heavily bombarded cells depend to a great extent on collection from the short-wavelength region of the solar spectrum. Considering this, the comparative measurements for bombarded and unbombarded cells indicate that simulator 1 has more energy in the short-wavelength region of its spectrum than all the other simulators, whereas simulator 2 has more energy in the long-wavelength region than the other simulators. Table IV contains a comparison of measurements of the bombarded cells made with simulators 1 and 2, which further confirm this conclusion.

The significance of this analysis lies primarily in its pinpointing a weakness in the design of the single- or dual-light-source simulator with fixed filters. Such simulators cannot possibly reproduce the solar spectrum accurately throughout the 0.35- to 1.1-micron region. Should measurements indicate that corrections have to be made in specific wavelength regions in the spectrum of these simulators, costly redesign and recalibration would be involved. Replacement of light sources for these simulators is also costly and involves recalibration. In the course of time, the spectral content of these simulators will shift because of the aging of light sources. Other problem areas associated with these simulators are not fully known because of the limited industrial experience with such simulators.

ADVANTAGES OF FILTER-WHEEL SIMULATOR

Measurements made on the filter-wheel simulator do not depend on the spectral content of the tungsten light source; therefore, light bulbs can be replaced without any recalibration, and the aging of bulbs is not significant. If measurements indicate inaccuracy in any region of the spectral calibration, the corrective process is strictly of a mathematical nature and involves a change of the factors applied to ratios of currents obtained for two cells under a specific filter or filters (ref. 1).

These advantages of the filter-wheel simulator and the good agreements obtained between BTL and Lewis simulators and between the Lewis simulator and airplane measurements on solar cells make this type of simulator the most promising for adoption as the standard for solar-cell measurements.

There has been some concern about measurements made of proton-bombarded cells under the low illumination that prevails when the filter-wheel simulator is used. In reference 3 a large increase is reported in measured minority-carrier diffusion lengths in the base region of proton-bombarded cells when background illumination is increased.

Experiments have been made to determine the significance of this effect in introducing errors in the filter-wheel measurements of proton-bombarded cells. Ten-ohm-centimeter cells were bombarded with various fluxes of 10-Mev protons, and the short-circuit currents of these cells were measured by using the filter-wheel simulator and airplane flights.

Table V shows the observed discrepancies between filter-wheel and airplane measurements of cells bombarded with a dose of 3×10^{11} 10-Mev protons per square centimeter. Differences between airplane and Lewis simulator measurements ranging up to 2 percent are encountered for electron-bombarded cells. There is no report of any significant change in the diffusion length of electron-bombarded cells resulting from a change in illumination level. The 0- to 2-percent difference cited is, therefore, probably due to differences in cell temperature at the time of measurement and to inherent errors. As shown in table V, a maximum correction of 3 to 4 percent in measured short-circuit currents of proton-bombarded cells compensates for the low illumination of the filter-wheel simulator. This correction is fairly constant in the dose range 3×10^{11} to 1×10^{12} 10-Mev protons per square centimeter, as shown in table VI. Doses above 10^{12} protons per square centimeter are not of practical interest for most present-day solar-cell applications; however, for cells bombarded with 3.9×10^{12} 10-Mev protons per square centimeter, the correction to filter-wheel simulator readings rises to 9 percent, as shown in table VII. The better agreement between airplane values and values from simulators 1 and 2 for cells heavily bombarded with protons is noteworthy.

Although it is evident that the filter-wheel simulator measurements are in error for proton-bombarded cells, corrections for such cell measurements have been determined and can be applied.

TABLE V. - COMPARISON OF AIRPLANE AND SIMULATOR SHORT-CIRCUIT CURRENT OF PROTON-BOMBARDED SILICON CELLS

[Dose, 3×10^{11} 10-Mev protons/sq cm.]

Cell	Airplane	Lewis simulator	Maximum correction, percent (a)
	Short-circuit current, ma		
1	36.3	34.7	4.6
2	53.9	52.3	3.1
3	39.7	38.4	3.4

[a]Standard correction on electron-bombarded cells, 1 to 2 percent.

TABLE VI. - COMPARISON OF AIRPLANE AND SIMULATOR SHORT-CIRCUIT CURRENT OF SILICON CELLS

[Dose, 1×10^{12} 10-Mev protons/sq cm.]

Cell	Airplane	Lewis simulator	Maximum correction, percent
	Short-circuit current, ma		
1	35.5	34.1	3.9
2	35.5	34.0	4.2
3	30.3	28.8	4.9

TABLE VII. - COMPARISON OF SIMULATOR SHORT-CIRCUIT

CURRENT OF SILICON CELLS

[Dose, 3.9×10^{12} 10-Mev protons/sq cm.]

Cell	Simulator 1	Simulator 2	Lewis simulator	Airplane
	Short-circuit current, ma			
1	55.9	53.5	50.9	----
2	37.8	36.4	33.4	----
3	38.8	37.2	34.44	38.4
4	47.4	46.2	41.1	----
5	37.5	36.2	33.69	36.5

VERSATILITY OF FILTER-WHEEL SIMULATOR

Another aspect of solar simulators is versatility. In this aspect the filter-wheel simulator far outranks other simulators. The filter-wheel simulator converts to an instrument for the analysis of spectral response, performance of antireflective coatings, and behavior of bombarded solar cells with only slight modifications.

Figure 1 presents an analysis of the improvements obtained with two types of antireflective coatings on solar cells. The analysis is made by comparing bare-cell and coated-cell outputs under illumination passed through each filter of the solar simulator. Shown in figure 2 are plots of the variation of cell currents for each filter as a function of 1-Mev-electron bombardment dose for uncoated solar cells. The currents collected for specific regions of the solar spectrum vary with bombardment dose and with cell type. It would be desirable for engineers using the cells to specify the maximum dose anticipated for a particular mission in space; thus, the solar-cell manufacturer could tailor his antireflective coating to produce maximum output current of a specific cell type at the specified dose. This could be readily accomplished by the use of filter-wheel simulator data similar to those shown in figures 1 and 2.

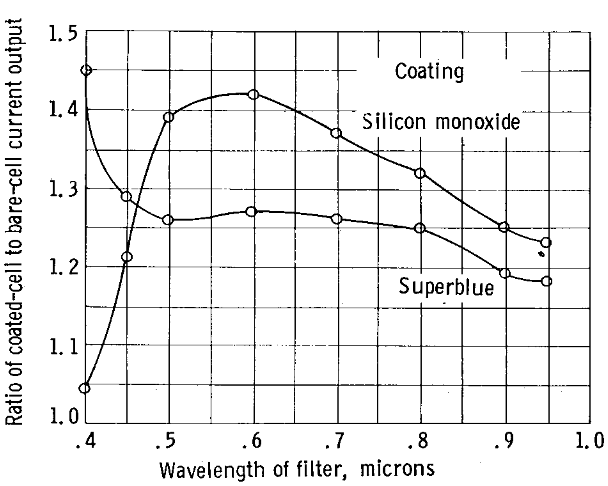
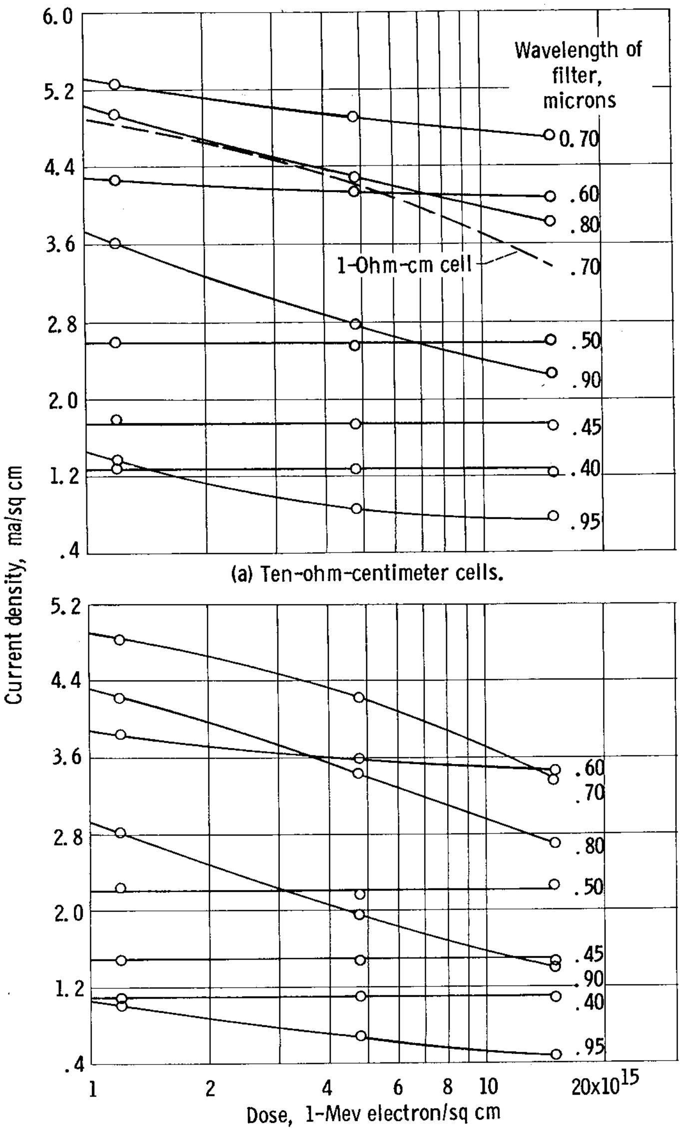


Figure 1. - Effect of antireflective coatings on current output.

The final aspect of solar simulators that will be considered is cost. The cost of the Lewis filter-wheel simulator is \$3000. Basic units of other simulators cost \$15,000 to \$20,000. The maintenance costs of the filter-wheel simulator are negligible compared with those for the other simulators. It is estimated that for an additional \$12,000 to \$15,000 electronic equipment and conveyer belts could be installed and modifications could be



(a) Ten-ohm-centimeter cells.

(b) One-ohm-centimeter cells.

Figure 2. - Current for specific regions of solar spectrum. High-blue boron-doped cells (uncoated).

TABLE VIII. - SHORT-CIRCUIT CURRENT OF GALLIUM ARSENIDE CELLS IN SIMULATOR AND IN AIRPLANE

Wavelength of filter, microns	Cell 1		Cell 2		Cell 3	
	Short-circuit current, ma					
0.95		0.15		0.16		0.15
.9		.94		1.07		1.06
.8		10.52		10.69		10.33
.7		8.56		8.47		8.26
.6		5.05		4.92		4.82
.5		2.06		1.97		1.93
.45		1.07		.99		.95
.4		.82		.79		.68
	Total	29.17	Total	29.06	Total	28.18
Airplane		30.2		30.0		29.6

TABLE IX. - SHORT-CIRCUIT CURRENT OF GALLIUM ARSENIDE CELLS IN SUNLIGHT

Cell	Sunlight intensity, mw/sq cm	Short-circuit current, ma	Calculated short-circuit current for 100 mw/sq cm intensity, ma	Error, percent
1	86.3	22.4	26	
	89.7	23.7	26.4	1.02
	96.7	24.5	25.4	
2	86.4	23.9	27.6	
	90.3	24.1	26.6	1.09
	95.0	24.0	25.2	
3	84.5	22.9	27.2	
	90.3	22.9	25.4	1.11
	91.2	22.9	25.1	
	94.5	23.0	24.4	

made to the basic filter-wheel unit so that the currents and power outputs of cells could be punched on IBM cards at the rate of a thousand per day. The design of the filter-wheel simulator for production measurements would be similar to the design first developed at BTL because the BTL system used rapid non-equilibrium measurements under each filter. The Lewis filter-wheel simulator uses equilibrium measurements and is therefore slower. The Lewis simulator is most desirable as a laboratory standard and as an economical instrument for the analysis of the characteristics of cells.

Although the Lewis simulator was calibrated for silicon solar-cell measurements, values of short-circuit current for gallium arsenide cells measured by using the simulator agree well with airplane-flight measurements, as shown in table VIII. The spectral response of the gallium arsenide cells can be compared with that of the silicon superblue cell shown in table I by comparing current values of the cell under each filter. The spectral response of the gallium arsenide cell may make extrapolations of sunlight measurements to higher intensities invalid, as shown in table IX. This partially accounts for the discrepancies continually reported between sunlight measurements made of gallium arsenide cells at various laboratories. The current of these cells is extremely sensitive to the presence or absence of certain absorption bands in the atmosphere.

CONCLUDING REMARKS

There has been little industrial experience with commercially marketed simulators for solar-cell measurements; however, many difficulties in calibration and maintenance of such simulators have been anticipated and are being realized.

The filter-wheel simulator has numerous advantages when compared with commercial simulators. Furthermore, good correlation has been obtained between filter-wheel simulator measurements and airplane-flight measurements.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 1, 1964

REFERENCES

1. Gummel, H. K., and Smits, F. M.: Evaluation of Solar Cells by Means of Spectral Analysis. Bell System Tech. Jour., vol. 43, no. 3, May 1964, pp. 1103-1121.

2. Brandhorst, Henry W., Jr.: Airplane Testing of Solar Cells. Proc. Fourth Annual Photovoltaic Specialist's Conf., Inter. Agency Advanced Power Group, IEEE, AIAA, and NASA Lewis, Cleveland (Ohio), June 2-3, 1964.

3. Denney, J. M., and Downing, R. G.: Charged Particle Radiation Damage in Semiconductors, IX: Proton Radiation Damage in Silicon Solar Cells. (NASA CR-55829), Space Tech. Labs., Inc., Aug. 31, 1963.

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